Systems Integration and Validation of an Automated Transmission for the Ohio State

EcoCAR 3 Vehicle

Undergraduate Thesis

Presented in Partial Fulfillment of the Requirements for the Degree Bachelor of Science

in the College of Engineering of The Ohio State University

By

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Abstract

The Ohio State EcoCAR Team is a student project team competing in Advanced Vehicle Technology Competitions, sponsored by the US Department of Energy. From August 2014 to May 2018, the EcoCAR team competed in the EcoCAR 3 Competition, additionally sponsored by General Motors. During the 4-year design cycle, teams were tasked with redesigning a 2016 Chevrolet Camaro to reduce its environmental impact while maintaining the performance expected from an American muscle car. The competition evaluates the participating team vehicles in events designed to measure fuel economy, emissions, vehicle performance, and overall consumer acceptability.

A Systems Engineering approach was used for development of the Ohio State EcoCAR 3 Camaro. This work focuses on two areas, the transmission and the clutch. Magnets and Hall Effect sensors were used to create a positional feedback system for the custom automated manual transmission. Additionally, computer aided design was used to design a mounting strategy for the slave cylinder, allowing for proper actuation of the clutching system. The requirements for these components were derived from higher level systems with top-level requirements based on competition performance. Verification and validation was performed to ensure requirements were satisfied at each level before integration with larger subsystems. Using this systems engineering strategy, vehicle systems were validated successfully, resulting in first-place finishes in all four years of the EcoCAR 3 program.

Dedication

I would like to dedicate this work to my mom, for her unwavering love and support during my pursuit of higher education, my dad for the countless hours he invested to teach me everything I know about cars, Dr. Shawn Midlam-Mohler for the guidance he provided to my research, and the EcoCAR Team for giving me the best college experience I could have ever asked for.

Acknowledgments

I would like to thank Simon Trask for his assistance in outlining and formatting this work.

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Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

The future of the mobility and the automotive industry is continually trending towards more fuel efficient and environmentally friendly vehicles. This has led to an increasing level of electrification in vehicles on the road today. Hybrid vehicles have provided some of the answers to this increasing demand for increased efficiency and performance. They provide the potential for zero emission driving and propulsion energy produced from renewable sources, eliminating the need for fossil fuels. However, hybrids on the market currently are often found lacking in vehicle performance and are fighting to gain consumer acceptability. EcoCAR 3 strives to gain consumer acceptability for hybrid vehicles in a high-performance atmosphere by creating a fast, fun, efficient, and eco-friendly Chevrolet Camaro.

1.1 The EcoCAR 3 Advanced Vehicle Technology Competition

EcoCAR 3 was the 11th iteration of the Department of Energy's (DOE) Advanced Vehicle Technology Competition (AVTC). EcoCAR 3, sponsored by the DOE and General Motors (GM). EcoCAR 3 challenged 16 universities across the United States and Canada to redesign a 2016 Chevrolet Camaro to improve fuel efficiency and emissions while maintaining the performance aspects and feel of an iconic American muscle car. This provided a foundation for research into new and emerging technologies in the automotive field, including hybrid powertrains and driver assistance systems.

The competition was a four-year process that lead teams along the Vehicle Development Process (VDP). This process mimics the Global Vehicle Development Process (GVDP) used by GM to efficiently use resources; including time, money, and developmental personal [3]. This process was adapted to fit the EcoCAR 3 schedule and is shown in Figure 1.1. The competition was divided into four segments, design, integration, refinement, and market engagement. It is important that the designs set out initially in Year 1 were carried through the entire process so the final product at the end of the cycle meets all the criteria set at the beginning of the project.

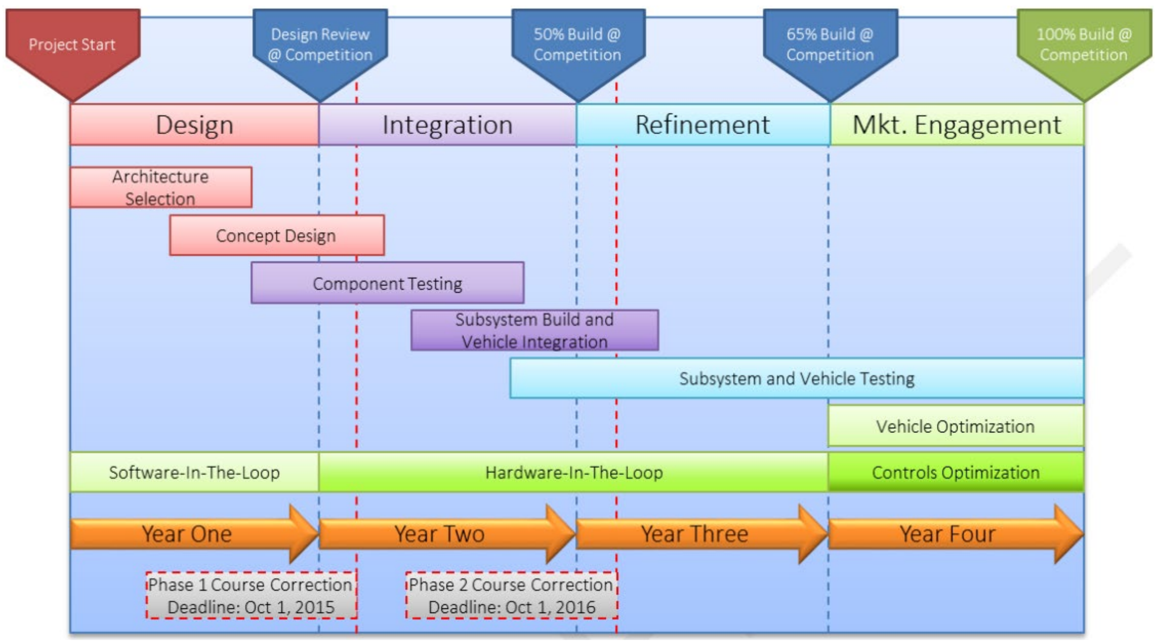

Figure 1.1: EcoCAR 3 Vehicle Development Process

Ohio State's EcoCAR 3 Vehicle

The Ohio State University (OSU) has a long-standing history of excellence in its participation in AVTCs. The EcoCAR 3 team consisted of approximately 50 students each year, ranging in experience from college freshman to Ph. D candidate. To participate effectively in competition, the team chose an architecture and set goals early in the design phase of the VDP.

Architecture

OSU selected a parallel-series, plug-in hybrid electric architecture to build onto their platform of a 2016 Chevrolet Camaro. The OSU vehicle contains an advanced energy storage system (ESS) and three torque sources while maintaining the rear-wheel drive configuration found in the stock Camaro. An overview of the architecture is in Figure 1.2

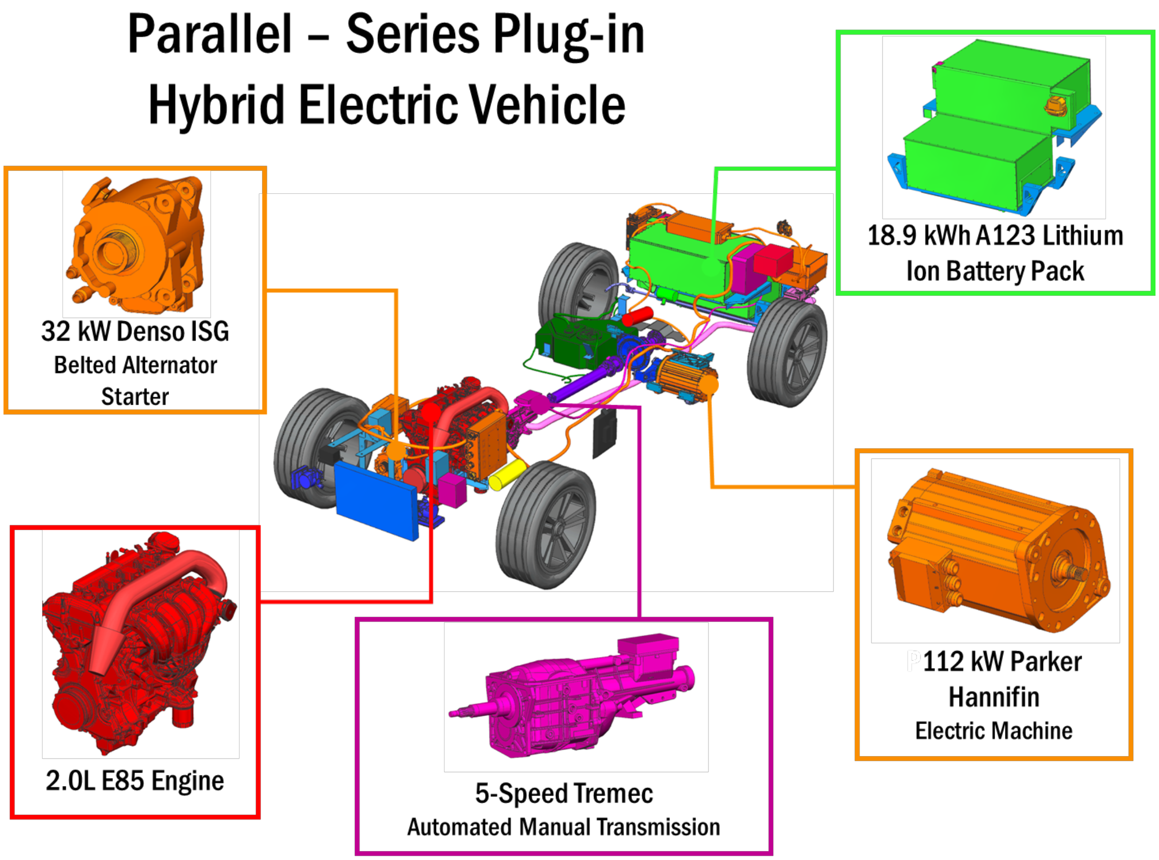

Figure 1.2: OSU Vehicle Architecture

Under the hood, the original engine was replaced with a downsized 2.0L E85 direct injection engine capable of providing torque to the rear wheels or generating electricity. Attached to the front of the engine was a belted alternator starter (BAS). These components were coupled to an automated manual transmission that sent torque to the rear differential. The rear of the vehicle also contained a large electric machine integrated into the driveline that provided all-electric driving capability. In the very rear of the vehicle, the ESS was implemented in a split-pack configuration to maximize battery volume while maintaining trunk space.

This highly versatile architecture allowed for three different driving modes that could be used to optimize energy consumption and emissions under many operating conditions. Modes included charge depleting (CD), charge sustaining (CS), and performance. In CD, the vehicle operates entirely on electric power from the rear electric machine (REM), consuming energy stored in the ESS. After depletion of the ESS's reserves, the vehicle switches to a CS mode, where the internal combustion engine (ICE) is used to either drive the vehicle or generate electricity. During all modes, regenerative braking was active to recapture the kinetic energy of the vehicle, reducing the demand on the vehicle's friction brakes and recovering battery state of charge (SOC).

High Level Goals

The Ohio State EcoCAR Team consistently sets high standards for themselves. In the scope of competition, the team aims to finish in the top five. Therefore, all points in the competition are relevant and the team must build a balanced vehicle capable of competing well in all events. The OSU vehicle is built with the mentality that it should maximize performance in the events that are weighted the most heavily. In this competition, OSU had chosen to focus their efforts on energy and emissions performance, while maintaining competitive vehicle performance in other areas, such as acceleration. The vehicle was built with as much versatility as possible to ensure that all events could be attempted in some capacity in the event of a component failure. This gave the team the best chance for success.

1.2 Organization of Thesis

The remainder of this thesis will be organized as follows:

Chapter 2 is a literature review concerning the motivations for the systems engineering approach and how it can benefit the life cycle of a project through a standardized work flow process.

Chapter 3 will be a closer look at how systems engineering will be applied to this research. The systems engineering V-Model will be broken down into three stages; decomposition and definition, design and implementation of components, and validation and verification. This provides an outline of how this project utilized systems engineering tools.

Chapter 4 details the decomposition and definition of the entire system, as well as the subsystems and components that it is broken into. Subsystem and component selection will be justified, system operation will be defined, and component descriptions will be given.

Chapter 5 dives into the design and implementation of the solutions chosen to satisfy the requirements specified in Chapter 4. This includes the design, fabrication, and implementation of the magnets, hall effect sensors, and slave cylinder mounting.

Chapter 6 explains the validation process that verified that the components and subsystems meet all the design requirements laid out in Chapter 4.

Chapter 7 provides final conclusions on the process and recommends future work to improve the systems and processes used throughout the course of this research.

Chapter 2. Literature Review

Most problems today are complex and require non-trivial solutions. Often, a problem cannot be solved by a single component performing a single function. The solution requires the use of a system of components working together to produce results that are not obtainable from the components on their own. The components that constitute a system can include people, hardware, software, facilities, policies, and documents; all with their own functions and value. In a system, each component in that system is required or the functionality of the entire system is at risk. The performance of the system is increased beyond the sum of the individual component performance due to the value created by the relationship between the components working together [1].

2.1 Systems Engineering

"Systems Engineering is an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder's needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system's entire life cycle" [1]. This approach is used to ensure that the designs implemented are the correct solutions to a consumer's need. The process of systems engineering can be broken down into seven tasks.

- *State the Problem* - This includes top-level functions that the system must perform and mandatory requirements that the system must satisfy. The focus should be on *what* to do, not *how* to do it [1].

- *Investigate Alternatives* – This is essentially a brainstorming stage where numerous designs are created and evaluated based on potential performance, schedule, cost and risk. This analysis is initially computed based on estimates by design engineers but is refined and redone as more data becomes available. Possible designs are judged based on compliance of capability against requirements [1].

- *Model the System* – For any of the potentially feasible alternative designs, a model of the system is used to further investigate possibilities. A model can include physical analogs, analytic equations, state machines, block diagrams, functional flow diagrams, object-oriented models, computer simulations, and mental models. These models should describe both the product and the process necessary to achieve a customer solution. The most favorable models will be developed continually as the project progresses. Also, as a result of these models, new alternatives may be discovered that also require investigation [1].

- *Integrate* – Every system is a group of subsystems or components working together. These subsystems will need to interact with each other for the whole system to function. Therefore, the interfaces between subsystems must be designed so work and information may be transferred between subsystems. If a subsystem is well designed, it only transfers finished products to other subsystems. “Feedback loops around individual subsystems are easier to manage than feedback loops around interconnected subsystems”[1].

- *Launch the System* – The system must be operated and allowed to do what it was intended to do. The preferred alternative is designed in detail and the interfaces between the designed system and its environment are considered. Consideration must be given to the humans, facilities, software, and other systems that the new system will come in contact with. Also, in this stage, the requirements of the system need to be validated and verified to answer the two questions, “Are we building the right system?” and “Are we building the system right?”[1]

- *Access Performance* – After the system is operational, its performance must be evaluated based on the figures of merit, technical performance measures and metrics that were defined at the onset of the project. These are used to ensure that the product meets the original intent of the design and will satisfy the intended customer [1].

- *Re-evaluate* – Throughout the entire design process, a continual string of re-evaluations is carried out. After each step, the outputs of a subsystem, component, process, or design are re-evaluated to ensure that they are performing as intended. This re-evaluation is used to modify the system, the inputs, the product, or the process to better achieve the desired result [1].

2.2 The V-Model

The life cycle of a system can be represented by the systems engineering V-Model. An example of the V-Model is given in Figure 2.1.

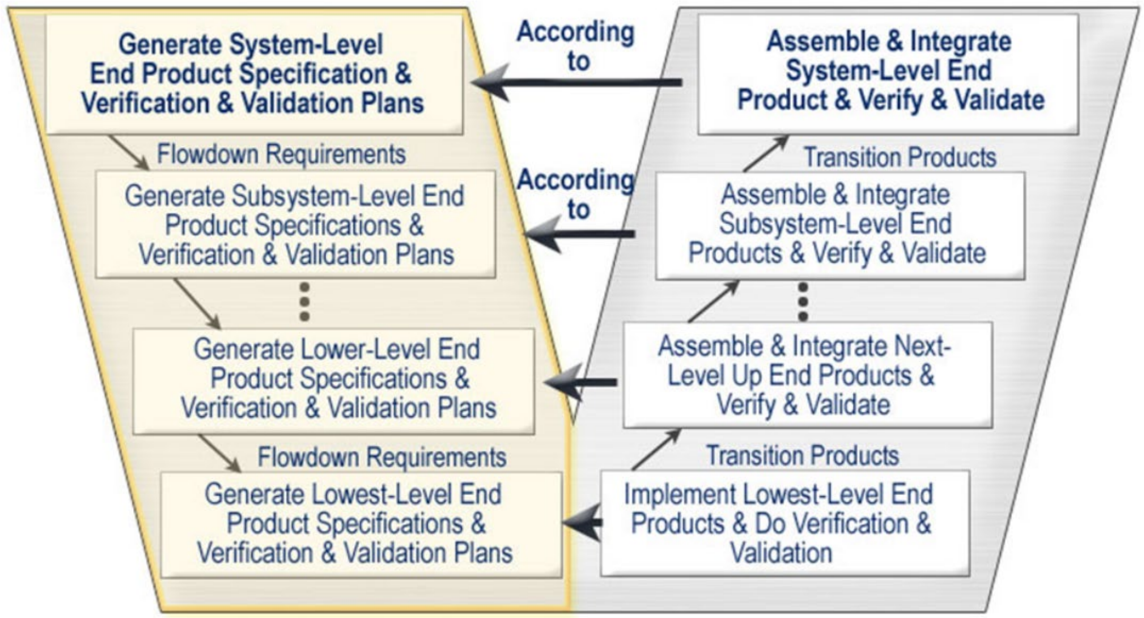

Figure 2.1: The Systems Engineering V-Model [2]

As a process, the V-Model "involves a sequential progression of plans, specifications, and products that are baselined and put under configuration management" [2]. The project life cycle progresses from the left to the right, following the "V" shape. The left side of the "V" progresses through the decomposition of requirements of the system into subsystem and component requirements, and the creation of system and subsystem specifications. The right side of the "V" follows the integration of components into subsystems and subsystems into the whole system. At each step of implementation, requirements for components and subsystems are verified before moving to the next step of validation. Following this process provides guidance for planning and implementation of system projects and helps accomplish the following objectives [2].

- *Minimize project risk* – Early recognition of planning deviations and risks improves process management and reduces risk [2].

- *Improve and guarantee quality* – Through specific requirement definition and mapping specific verification strategies to requirements, the final design better solves the initial problem. This reduces unnecessary engineering and rework [2].

- *Reduce total cost of project and system life cycle* – Defining all system and subsystem requirement early, the necessary validation can also be planned out and a better idea of the entire budget can be calculated, estimated, and controlled [2].

- *Improve communication with stakeholders* – The standardized method of defining requirements and validation strategies improves knowledge transfer and promotes a mutual understanding of the system between engineers and stakeholders. There is less time and effort lost on miscommunication [2].

> "The V-Model process emphasizes requirements-driven design and testing. All design elements and acceptance tests must be traceable to one or more system requirements and every requirement must be addressed by at least one design element and acceptance test. Such rigor ensures nothing is done unnecessarily and every that is necessary is accomplished" [2].

Chapter 3. The Systems Engineering Approach

A Systems Engineering approach was taken to address the integration concerns of the EcoCAR 3 vehicle. The process used in this research follows the V-diagram shown in Figure 3.1. The V-diagram contains two sides, a decomposition and definition side on the left, and an integration, validation, and verification side on the right. The left and right sides of the V-diagram are aligned so that the requirements on the left are validated by the corresponding checks on the right. This provides for traceability from components and subsystems to the original requirements of the system.

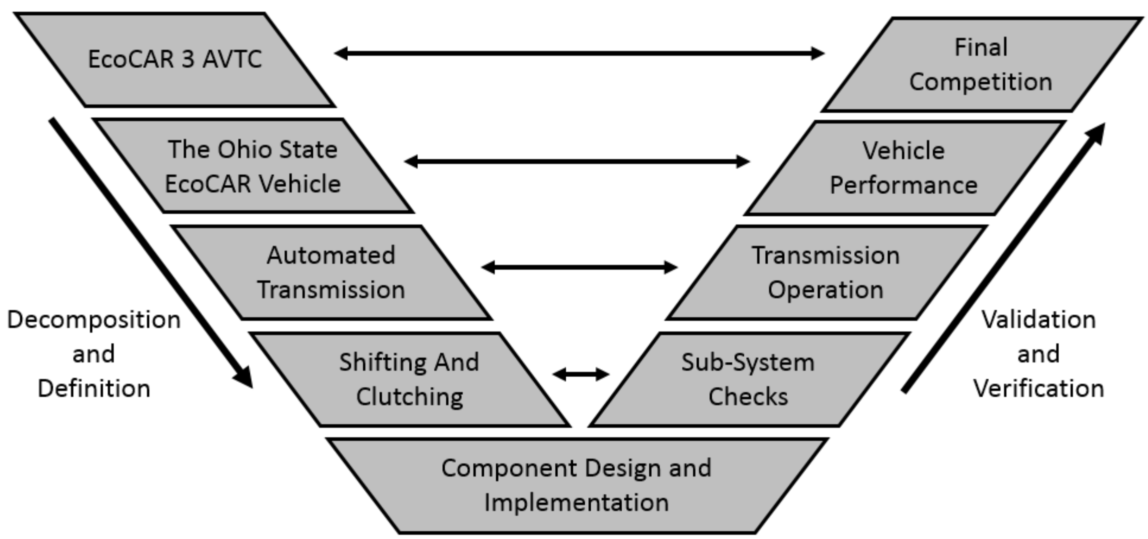

Figure 3.1:EcoCAR V-Diagram

3.1 Decomposition and Definition

On the left side of the V-diagram, the overall system is decomposed, and each level is discussed in detail. The levels of the system include:

- The EcoCAR 3 Competition
- OSU EcoCAR vehicle
- Automated transmission
- Automated shifting and clutching
- Individual components.

Each subsystem has requirements that must be met for the system to function as intended. Requirements were specified in order of increasing degree of specificity, working their way down from competition level to component level. As subsystems are identified, they must be completely defined and potentially broken down further into smaller subsystems, each with their own set of requirements. Subsystem and component requirements must be derived from a previous requirement. This allows low-level design decision to be traced backward through requirements to ensure that they are all working towards the final goal of the system. Once subsystems have been broken down into components performing singular functions, designs can be created to solve individual problems.

3.2 Component Design and Implementation

After defining the requirements of the system, solutions are engineered to satisfy each of the requirements laid out previously. For the OSU EcoCAR vehicle, the components that were designed included a system for positional feedback from the transmission shifter and a method for mounting the slave cylinder. Initial designs were drawing using computer aided design (CAD) software and engineering drawings were generated to aid in fabrication. Both subsystems were fully integrated into the vehicle.

3.3 Validation, and Verification

On the right side of the V-diagram, subsystems are put back together and tested to ensure final operation of the overall system. Each problem area, defined on the left, required a solution to be designed, implemented, and validated. Components were designed, fabricated, and integrated into subsystems. After design and implementation of a component or subsystem, verification was performed to ensure the design requirements previously specified are satisfied. A component or subsystem must satisfy all associated requirements prior to being integrated into a larger subsystem. This ensures that only fully functional subsystems are integrated and thus reduces the risk of a larger subsystem failing.

Starting at the component level, checks were performed to ensure that each component met the corresponding component requirements. Subsystem checks were performed to ensure that the shifting and clutching requirements were satisfied. Transmission operation checks were performed to ensure the automated transmission requirements were satisfied. Vehicle performance was evaluated to satisfy Ohio State EcoCAR Vehicle requirements. Final competition was attended to validate system level requirements and prove that the Ohio State EcoCAR vehicle was built as it was originally intended.

Chapter 4. Decomposition and Definition

In this chapter, the requirements of the overall system will be broken down into corresponding subsystems. The decomposition and definition side of the V-diagram is the first stage in the Systems Engineering Approach. This area of focus is highlighted in Figure 4.1.

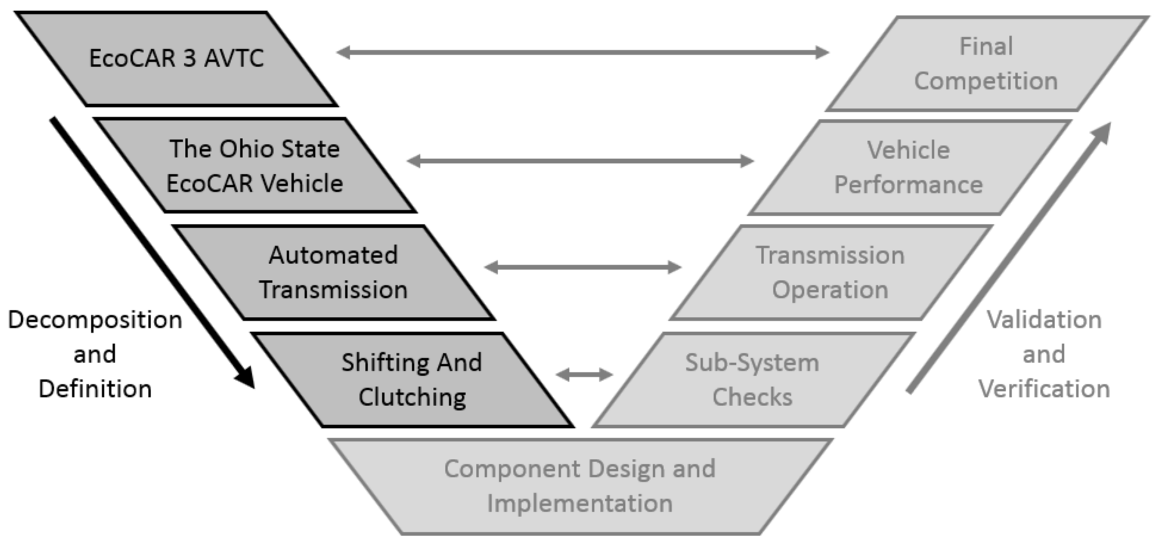

Figure 4.1: Decomposition and Definition in the V-Diagram

4.1 The EcoCAR 3 Competition

At the highest level, the EcoCAR 3 teams are competing in a competition with the intent to win. Therefore, Requirement (1) for teams participating in the competition is as follows.

(1) Competition teams shall strive to win in each of the four years of competition.

Each year the competition is scored out of 1000 points and the school with the most points at the end of the competition is acknowledged as the winner. Points are allocated through a variety of sources throughout competition including pre-competition reports, dynamic events and technical presentations. To win the entire competition, it is important for the Ohio State Team to perform well in all competition events. The competition events that were heavily impacted by this research include:

- IVM – 60 MPH Acceleration Event
- Consumer Appeal Event
- Emissions and Energy Consumption Event

These events evaluate the requirements set forth by the competition for performance, consumer acceptability, energy consumption, and emissions. Requirements for this research were derived from the need to perform well in these events.

IVM – 60 MPH Acceleration Event

This competition event would evaluate the vehicle's ability to accelerate from a stop to 60 MPH. The event is carried on a long, straight, level surface. The vehicle is positioned at one end of the test area with the vehicle stopped. The event begins by depressing the accelerator pedal fully and allowing the vehicle to accelerate slightly beyond 60 MPH. Velocity and time were captured with a VBOX GPS system. The test also accommodated a 1' roll out. This event defines Requirement (2).

(2) The vehicles shall have sufficient longitudinal performance.

Consumer Appeal Event

The consumer appeal event placed judges from a variety of backgrounds in the driver seat of the teams' vehicles. Judges were given the opportunity to drive the Camaro in any manner they deemed appropriate and they evaluated the vehicle on its full range of drivability characteristics. This event defines Requirement (3).

(3) The vehicles shall have adequate drive quality.

Emission and Energy Consumption Event

The emissions and energy consumption (E&EC) event measured the vehicle's emissions production and energy consumption over the course of a standard drive cycle. To begin the event, the vehicle is prepared with full fuel and full ESS SOC. The event is driven by professional drivers on a pre-determined cycle that is constant for all teams participating. The drive cycle is also Utility Factor (UF) weighted to evaluate all-electric driving capability. This event defines Requirement (4).

(4) The vehicles shall be fuel efficient.

Requirements (2), (3), and (4) are derived from Requirement (1).

Considering the relevant dynamic events in combination with all other aspects of the competition, the OSU team further refines Requirement (1) and sets Requirement (5).

(5) The OSU team shall place in the top 5 in each year of the competition. [5]

4.2 OSU EcoCAR Vehicle

One of the tools used to assist in the design of a vehicle to perform well in competition events are the Vehicle Technical Specifications (VTS). Competition provides target VTS for all teams as design targets for the teams to strive towards. The OSU Team further develops these VTS targets to better align with Requirement (5).

Table 4.1: EcoCAR Vehicle Technical Specifications [1]

VTS	Units	Targets	Team VTS
Acceleration, IVM–60 mph	sec	5.9	7.5
Acceleration, 50–70 mph (Passing)	sec	7.3	8.0
Braking, 60–0 mph	ft	128	120
Acceleration Events Torque Split (Front/Rear)	%	RWD	RWD
Lateral Acceleration, 300 ft. Skid Pad	G	0.85	0.90
Double Lane Change	mph	55	55
Highway Gradeability, @ 20 min, 60 mph	%	6%	6%
Cargo Capacity	ft^3	N/A	2.4
Passenger Capacity	#	4	4
Curb Mass	kg	N/A	1903
Starting Time	sec	2	2
Total Vehicle Range	mi	N/A	273
CD Mode (blended/EV)		N/A	EV
CD Mode Range	mi	N/A	44
CD Mode Total Energy Consumption	wh/km	N/A	220
CS Mode Fuel Consumption	wh/km	N/A	558
UF-Weighted Fuel Energy Consumption	wh/km	N/A	504
UF-Weighted AC Electric Energy Consumption	wh/km	N/A	193
UF-Weighted Total Energy Consumption	wh/km	700	697
UF-Weighted Total Energy Consumption	mpgge	30.0	43.3
UF-Weighted WTW Petroleum Energy Use	wh PE/km	420	150.9
UF-Weighted WTW Greenhouse Gas Emissions	g GHG/km	225	300

To meet the Team VTS targets, the Ohio State Team defined Requirement (6).

(6) The OSU vehicle shall meet or exceed all Team VTS targets.

In addition to Requirement (6), the team defines the following Requirements to ensure excellent performance in the competition events.

(7) The OSU vehicle shall have an IVM – 60 time less than or equal to 7.5 seconds. [4]

(8) The OSU vehicle shall maintain the level of driver-vehicle interaction present in the production Camaro.

(9) The OSU vehicle shall minimize noise, vibration, and harshness (NVH).

(10) The OSU vehicle shall improve drive quality and overall driving feel.

(11) The OSU vehicle shall minimize total vehicle mass.

(12) The OSU vehicle shall maximize efficiency.

Requirement (7) focuses on improving the vehicles longitudinal performance and was derived from Requirement (2). Requirements (8), (9), and (10) focus on improving the vehicle's drivability and driver interaction and were derived from Requirement (3). Requirements (11) and (12) focuses on optimizing the vehicles performance in fuel efficiency and were derived from Requirement (4).

The OSU Team strives to achieve the best possible performance in each event and therefore sets these requirements to ensure that the team strives for optimized performance and not acceptable performance in each event.

4.3 Automated Transmission

The vehicle's transmission connects the front powertrain (ICE and BAS) to the rear wheels of the vehicle. The transmission must transfer of energy efficiently while minimizing weight impacts to the vehicle. The transmission needs to provide multiple gear ratio options, so the engine operating speed can be optimized for fuel efficiency. The gear ratios should also provide for a range of desirable potential operating speeds during normal operation to allow for desired engine speed to be commanded. This process should be seamless from the viewpoint of a driver and require no interaction while driving. This leads to Requirement (13), which is derived from Requirements (8) and (10).

(13) The vehicle's transmission shall appear as an automatic to the driver. [3]

The OSU EcoCAR utilizes an automated manual transmission and an automated manual clutch. The transmission was a Tremec T-5 5-speed manual transmission that was automated by the team. This automation allowed for complete control over the timing and process of the vehicle shift schedule. The clutch was mechanical dry clutch from a 2012 Ford Focus with the standard transmission option. The automation of this subsystem allowed for the engine to be decoupled at any time and provided control for the torque transmitted to the rear wheels. The result of the combination of these two subsystems is a transmission system that is completely automated from a driver perspective. The locations in the vehicle's drivetrain of the two systems are shown in Figure 4.2

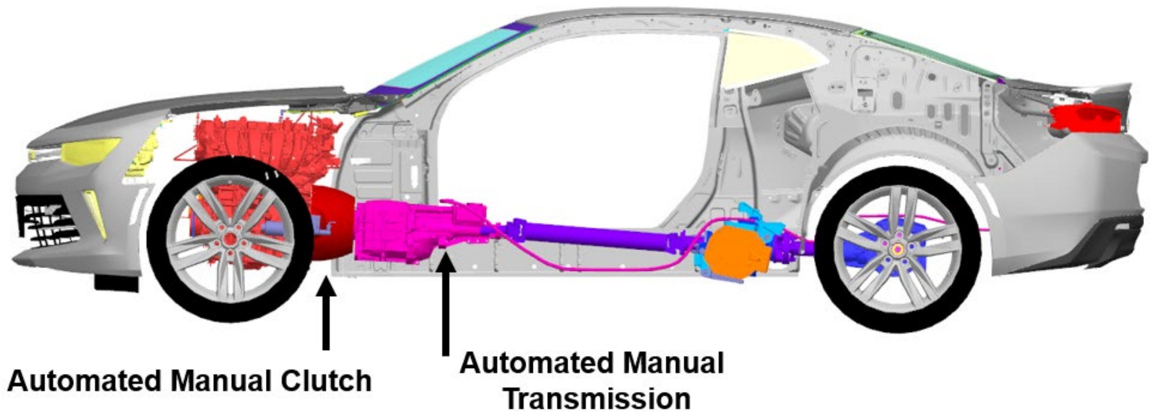

Figure 4.2: Component Locations in the OSU EcoCAR

4.4 Automated Shifting and Clutching

Before defining requirements for the shifting and clutching subsystems, their operation and functionality must be described.

Shifting Components and Operations

In a traditional manual transmission vehicle, the driver interacts with the transmission through the manipulation of the shifter. For this definition, it is assumed that the "transmission" mentioned is the 5-speed Tremec T-5 manual transmission used in the OSU EcoCAR vehicle. When driving, the driver may maneuver the shifter into one of the five gear locations that make up the H-pattern, shown in Figure 4.3. The orientation of the gear locations and motion of the shifter between each location can be decomposed into two potential directions. Therefore, the system has two degrees of freedom. These directions constitute the basis for a coordinate system that is later used to describe the motion of the system. The coordinate system can also be seen in Figure 4.3.

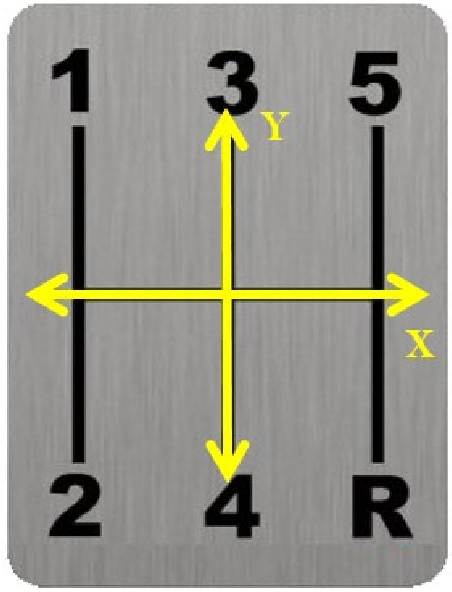

Figure 4.3: H-Pattern with Overlaid Coordinate System

The under-side of the shifter, invisible to the driver, is connected to a shifting block inside the transmission. This mechanism is connected to the shifter by a ball and socket joint in the middle and as a result, any motion made by the driver is inversely experienced inside the transmission. Figure 4.4. shows the shifter, ball and socket joint, and shifting block.

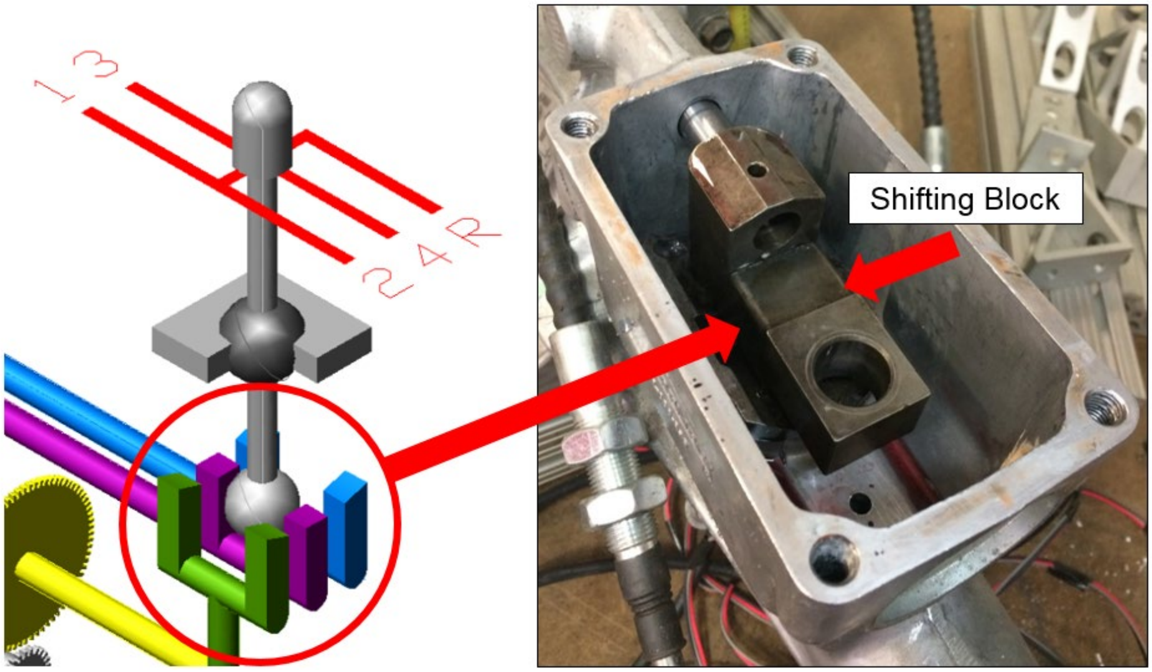

Figure 4.4: Shifting Block Location

The brown metal component in the image on the right in Figure 4.4 is the shifting block. The cylindrical hole in the center of the right image is the receiver for the bottom end of the shifter, which holds the sphere circled on the left. When the driver moves the shifter, corresponding motion on the other side of the shifter causes motion of the shifting block, resulting in the driver shifting the transmission into one of the gears on the H-pattern.

To automate the actuation of the manual transmission, the driver interaction must be replaced with an H-pattern converter and external actuators. The H-pattern converter is a mechanism that mimics the lower half of a shifter and is controlled with two levers. To fully actuate the system, it is required to have one actuator per degree of freedom. For the OSU EcoCAR, this was done with two DC motors used as rotational actuators, two 4-bar linkages, and long cables to connect the motors to the transmission. The long cables allow for remote mounting of the actuators. This was necessary due to space constraints near the transmission in the vehicle. The shifting actuators and mechanisms are shown in Figure 4.5

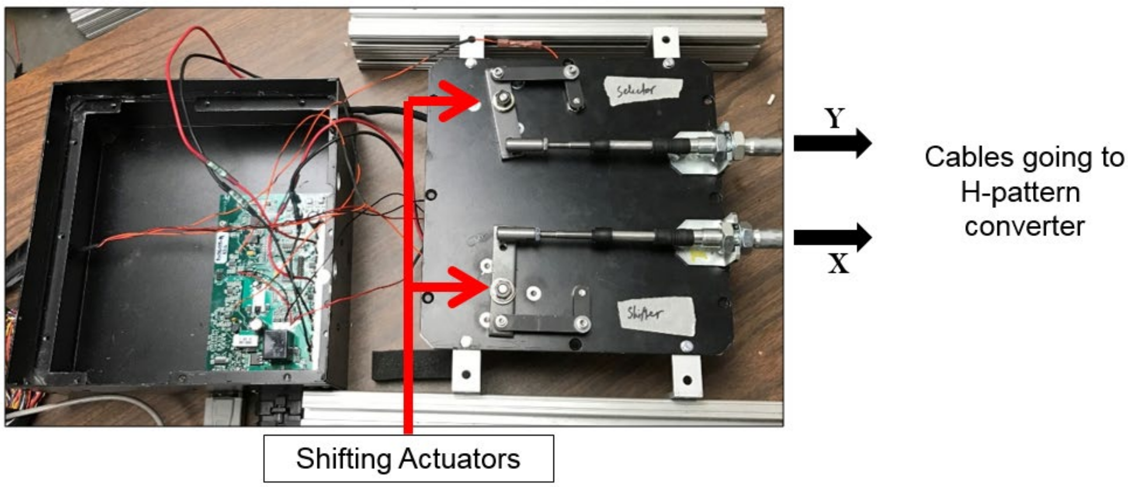

Figure 4.5: Shifting Actuators and XY Cable Ends

Pushing/pulling on the X/Y cables in sequence allow gears to be selected in the H-pattern.

Clutching Components and Operation

The purpose of a clutch system is to connect the output of the ICE to the input of the transmission. This system contains four main components: a flywheel, clutch disc, pressure plate, and slave cylinder. The flywheel is bolted to the engine and the pressure plate is bolted to the flywheel. Both components have large, flat, steel, friction surfaces on one face. The clutch disk is clamped in-between the friction surfaces on the flywheel and pressure plate. The center of the clutch disc is a splined connection that fits onto the input shaft of the transmission. These components are shown in Figure 4.6.

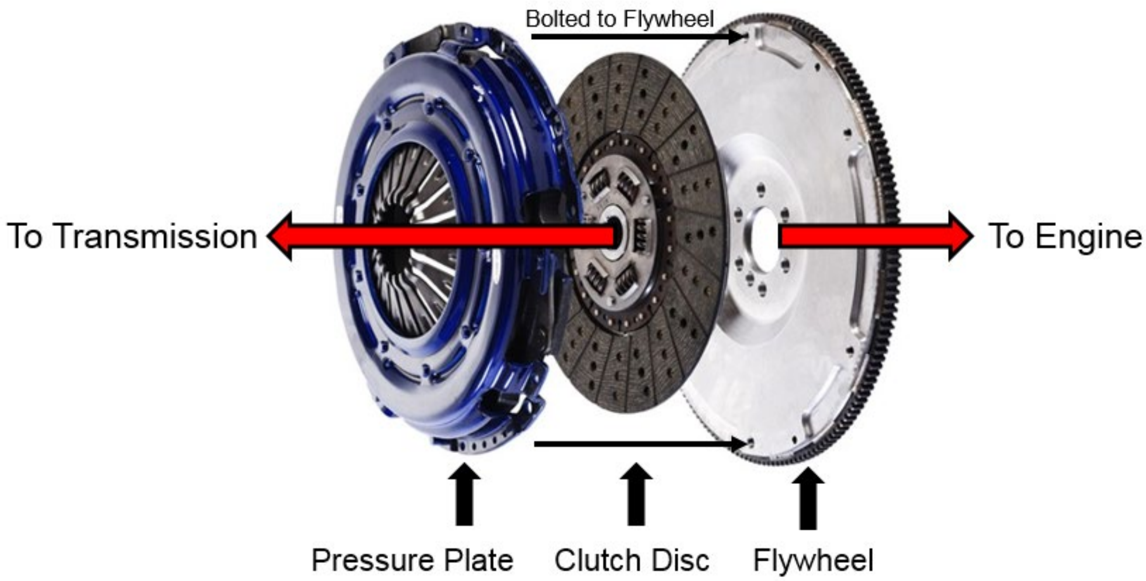

Figure 4.6: Component Definition and Torque Flow Through the Clutch System

Nominally, the pressure plate and the flywheel clamp tightly on the clutch disc and the entire system rotates at the same angular velocity as the engine. In this configuration, torque and speed are transmitted from the engine, through the clutch, to the transmission. When there is a need to disconnect the engine from the transmission, such as when the vehicle is stationary, or the transmission needs to shift gears, the clutch can be actuated to release the clutch disc and allow the two sides to spin independently. This is accomplished with the use of the slave cylinder, shown in Figure 4.7.

The slave cylinder is a hydraulic actuator that looks like the top image in Figure 4.7 when there is no fluid pressure and looks like the bottom image when pressure is applied. This motion actuates the pressure plate, causing it to pull away from and release the clutch disc.

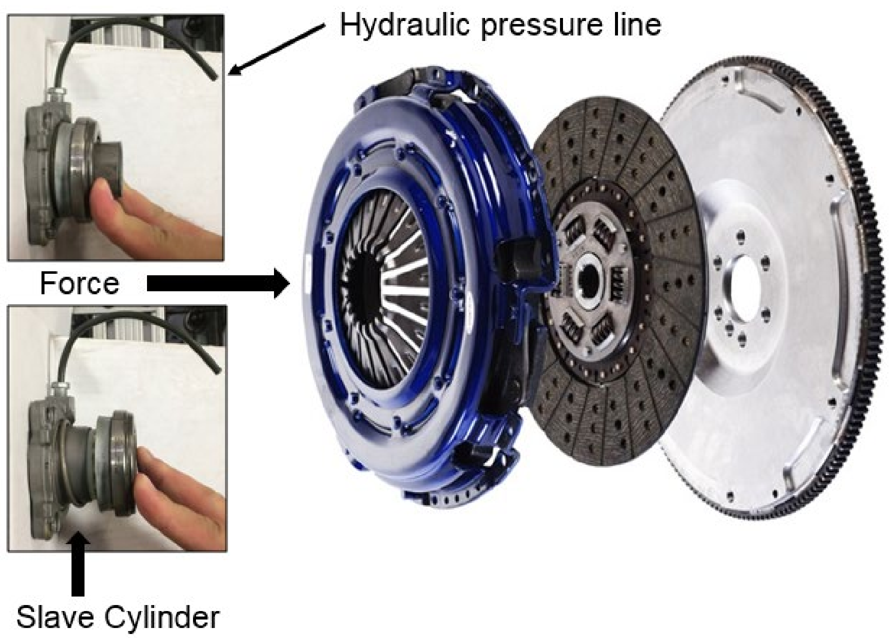

Figure 4.7: Slave Cylinder Operation

In a traditional manual vehicle, the driver's foot is used to press the clutch pedal, which compresses the master cylinder and supplies hydraulic pressure to the slave cylinder. In this manner, the driver is directly responsible for clutch position. The OSU team automates this system by replacing the driver's foot and the master cylinder with an electro-hydraulic actuator. This allows the clutch position to be determined electronically and the commanded signal could to be correlated to a transmissible amount of torque through the clutch. This system is shown in Figure 4.8.

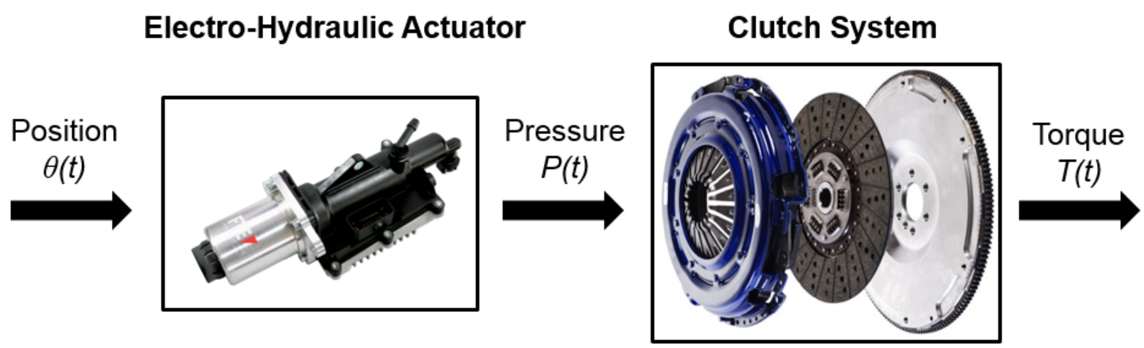

Figure 4.8: OSU EcoCAR Clutching System Diagram

With this system, the operation of the clutch can be fully controlled from the vehicle control strategy and requires no input from the driver.

Automated Shifting Requirements

The transmission operation was intended to satisfy three requirements.

(14) The transmission shall shift into all gears.

(15) The transmission shall pass torque in a controlled manner.

(16) The transmission shall function reliably [6].

Requirement (14) ensured that the transmission maintains full range of functionality after any modifications performed by the team and was derived from Requirement (12). Requirement (15) ensured that the transmission operation could be optimized by the team after implementation and was derived from Requirements (9), (10), and (12). Requirement (16) ensured that the transmission could continue to operate during all competition events, during all years of competition and was derived from Requirement (5).

Automated Clutching Requirements

The clutch operation was broken down into three main requirements.

(17) The clutch shall disconnect the engine from the transmission.

(18) The clutch shall pass torque in a controlled manner.

(19) The clutch shall function reliably.

Requirement (17) ensured that the vehicle can be operated in the modes that require the engine to be separate from the wheels and that the transmission can be shifted into another gear while not connected to the engine. This was derived from Requirement (13). Requirement (18) ensured that the clutch operation could be calibrated and controlled by the team and was derived from Requirement (9) and (10). Requirement (19) ensured that the clutch could continue to operate during all competition events, during all years of competition. This was derived from Requirement (5).

4.5 Components

There are two major component areas that were modified under the premise of this research. The first area was the integration of sensors to provide feedback to the transmission controller concerning the position of the shifting block. The second area was the integration of the slave cylinder into the clutching system. This required accurate mounting and spacing to ensure proper operation.

Sensor Integration

The requirements for the sensor integration included:

(20) Modifications shall not impede the range of motion of the shifting block.

(21) Modifications shall not compromise the integrity of the transmission case.

(22) Modifications shall not create any potential fluid leaks.

(23) The sensors shall provide data in all possible positions of the shifting block. [6]

Requirement (20) ensured that any modification made does not impede the operation of the transmission or prevent a gear from being selected. This was derived from Requirement (14). The range of motion necessary for the shifting block is shown in Figure 4.9. Requirements (21) and (22) ensured that any modification made do not compromise the safety of the system or create any hazardous situations. These were derived from Requirement (16). Requirement (23) ensures that the sensors chosen provided enough information about the transmission so that a feedback loop can be establishing the transmission control. This was derived from Requirement (15).

Slave Cylinder Mounting

The requirements for the slave cylinder mounting include:

(24) The mounting shall provide support for the slave cylinder during operation

(25) The mounting shall position the slave cylinder accurately so the range of motion of the slave cylinder and pressure plate correlate.

Requirement (24) ensured that the slave cylinder position will be maintained during operation of the vehicle and is derived from Requirement (19). Requirement (25) ensured that the clutch would be able to function appropriately after implementation on the vehicle. This was derived from Requirements (17) and (18).

A complete list of system requirements can be found in Appendix A.

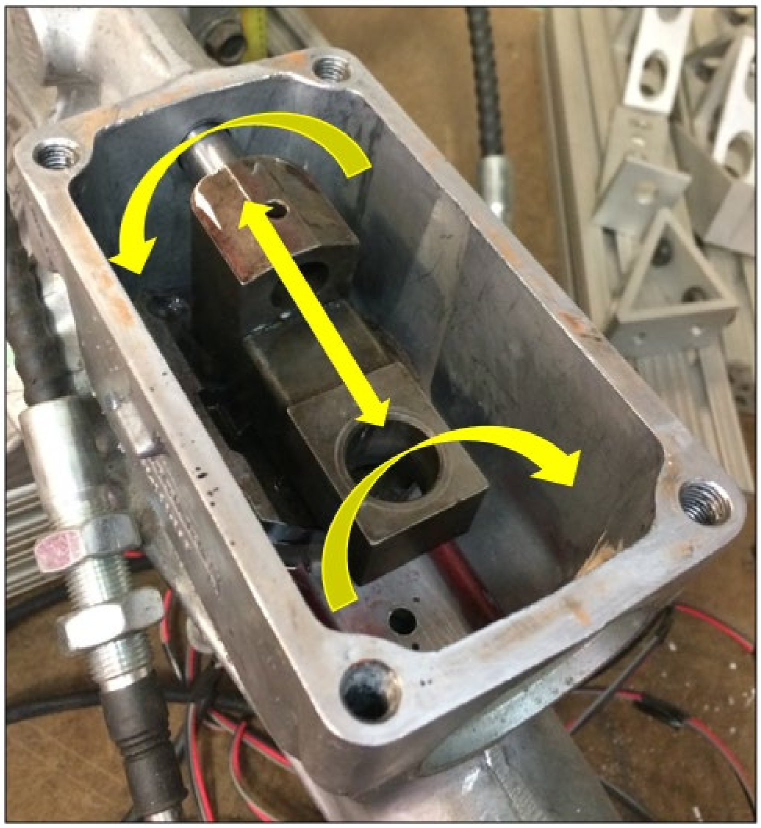

Figure 4.9: Shifting Block Range of Motion

Chapter 5. Component Design and Implementation

In the component design and implementation stage, solutions are engineered to solve the problems that were presented during the decomposition and definition stage. Here, the requirements defined previously are used to drive engineered solutions. The component design and implementation bottom of the V-diagram is referred to as the second stage in the Systems Engineering Approach. This area of focus is highlighted in Figure 5.1.

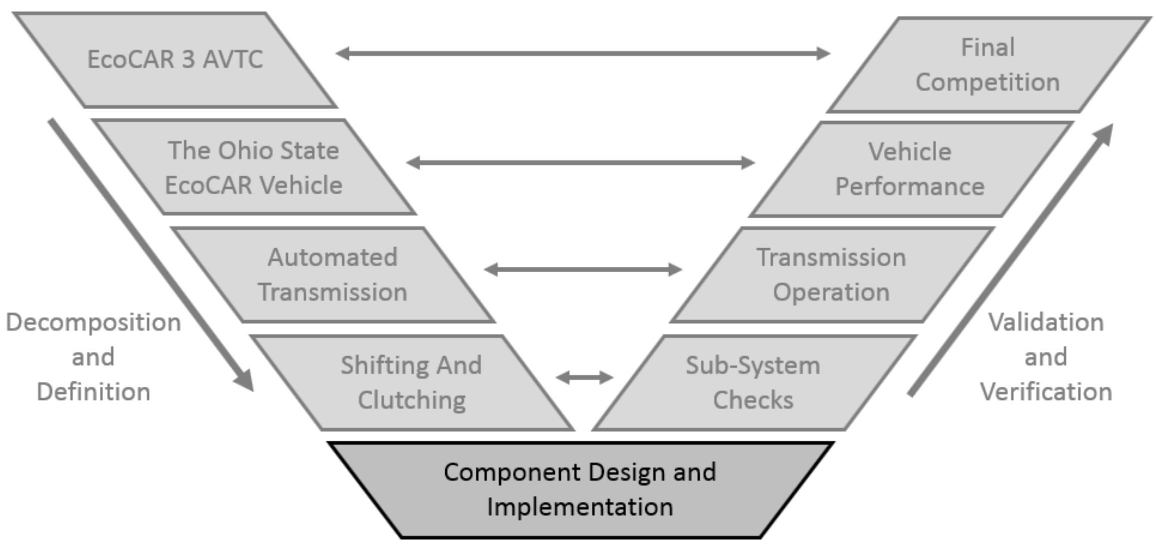

Figure 5.1: Component Design and Implementation Stage Of the V-Diagram

5.1 Magnet and Hall Effect Sensor Integration

To satisfy Requirements 38(20) - (23), magnets and Hall Effect sensors were implemented for feedback control in the transmission. This solution was favorable because a change in magnetic field can be detected through the aluminum of the transmission case, minimizing the level of intrusion that this sensing system would cause. A changing magnetic field creates an analog signal output from a Hall Effect sensor, and therefore, the exact distance of a magnet from a sensor can be determined.

The stack shown in Figure 5.2 represents how the magnets were implemented onto the shifting block. These magnets were chosen for their field density and small size. They were stacked to maximize the field strength while maintaining the clearances around the shifting block. The specifications of the magnets chose can be found in Table 5.1. Due to space constraints, a stack of three magnets was used on one side of the shifting block and a stack of two magnets was used on the other side.

Figure 5.2: Three Magnet Stack

Table 5.1: Magnet Specifications (Single Magnet)

	Value	Unit
Grade	N35	-
Field Strength	2076	Gauss
Height	0.188	Inch
Diameter	0.750	Inch

The potential positions of the shifting block are shown in Figure 5.3. All positions must be represented in the output of the sensors. Therefore, the potential magnet positions are given in Figure 5.4. Due to limited magnetic field strength, one magnet per side is required. To increase sensor fidelity and provide measurement redundancy, four magnets were chosen. The orientation was determined by space available inside the transmission and to maximize a single sensor's output in one of the shifting block's extreme positions.

Figure 5.3: Gear Locations Relative to the Shifting Block

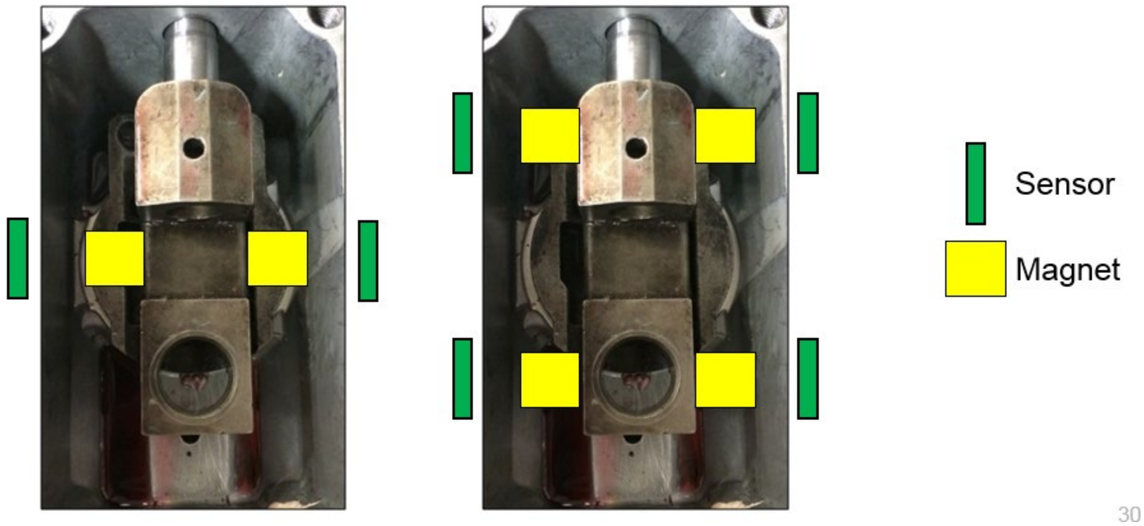

Figure 5.4: Potential Magnet Locations

The shifting block base material was steel, and the magnets already mostly held their position relative to the shifting block. However, aluminum covers were designed and fabricated to hold the magnets in place on the shifting block, preventing incidental contact and ensuring that the magnets maintain their position throughout the life cycle of the vehicle. This was critical because the combined sensor outputs were calibrated to relate a unique magnetic field with a certain shifting block position. If the magnets were to shift during operation, the calibration would be rendered useless and the system would likely fail.

The covers were initially designed in SolidWorks and an engineering drawing of these is shown in Figure 5.5. The drawing was divided into two sections corresponding to the two machining operations necessary to fabricate the covers.

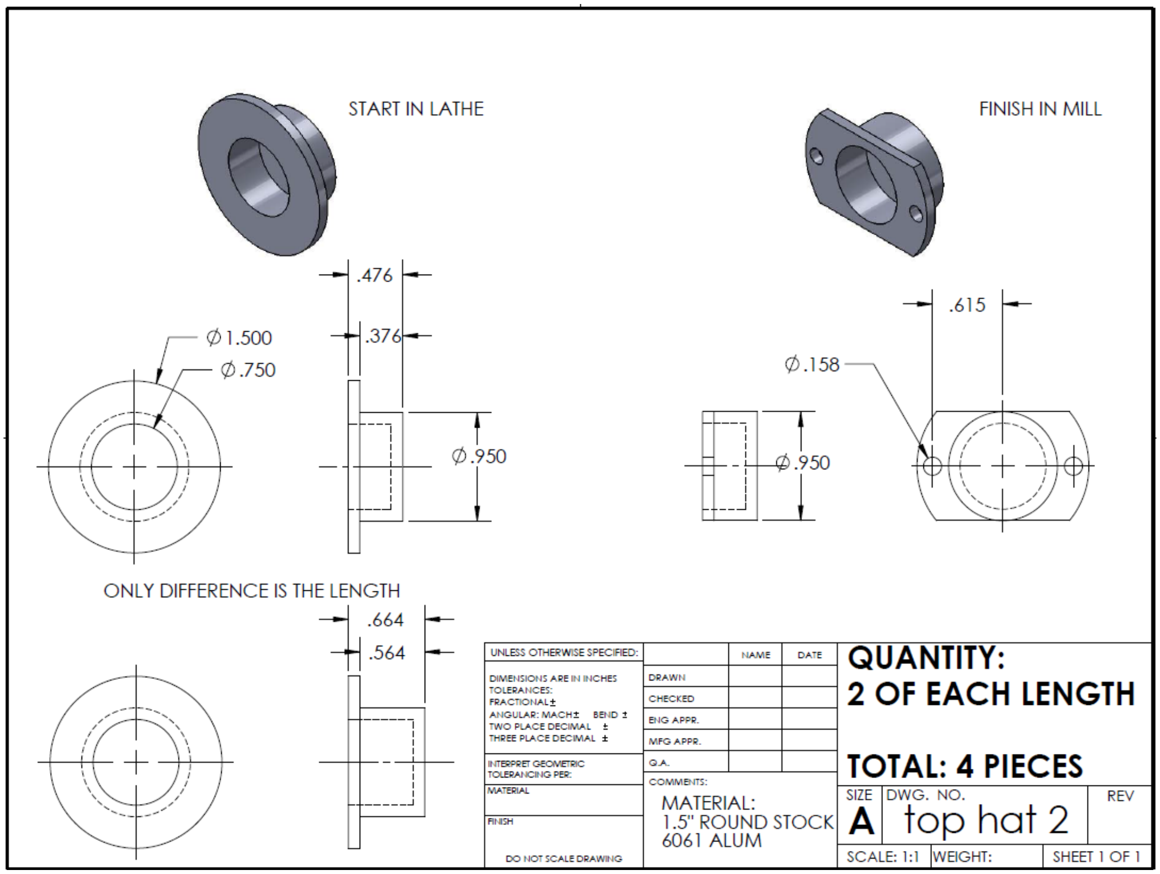

Figure 5.5: Engineering Drawing for Manufacturing of Magnet "Hats"

The first machining operation utilized a lathe to turn down raw material stock. The second operation utilized a milling machine to add the final features. This drawing also provided the dimensions for both the two and three magnet stacks. Figure 5.6 shows the final manufactured parts that would be implemented on the vehicle. The corresponding stack of magnets fit inside the hat's with less than 0.010" clearance. After machining, the magnets were inserted into the covers and epoxied onto the shifting block. Originally, the covers were intended to be bolted and epoxied for multiple layer positional security. However, due to timeline constraints, the components were only epoxied.

Figure 5.6: Final Manufactured Magnet "Hats" (Left: Bottom View. Right: Side View)

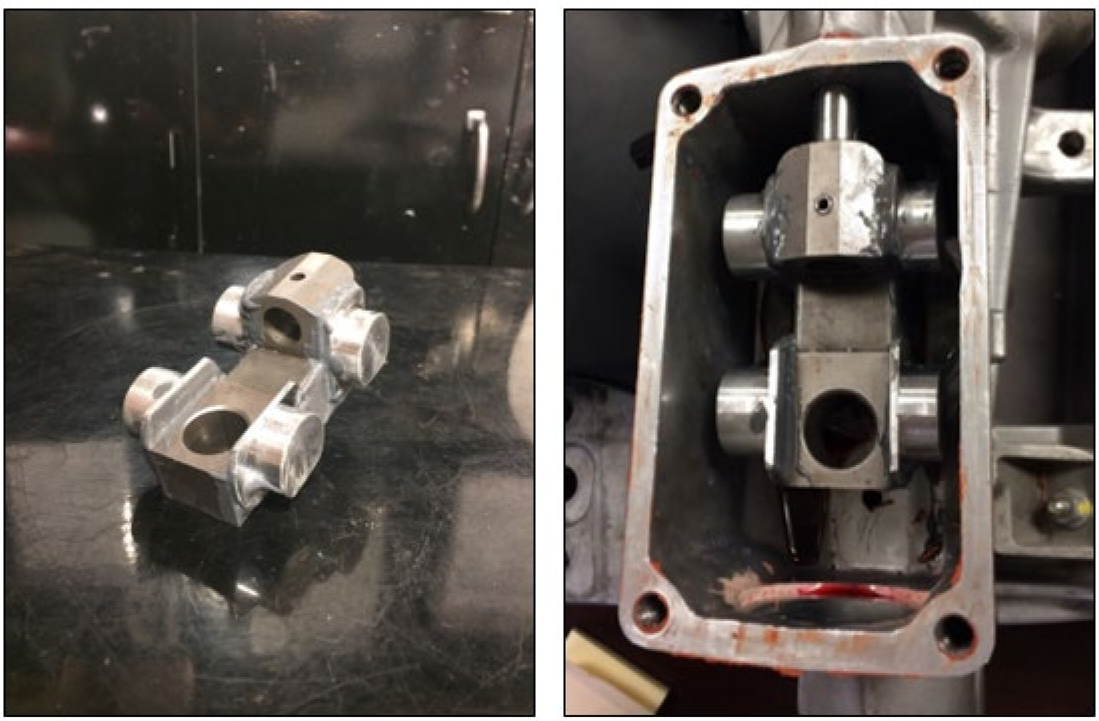

Figure 5.7: Final Assembly of Magnets onto Shifting Block

5.2 Slave Cylinder Mounting

To satisfy Requirements (24) and (25), an appropriate mounting strategy for the slave cylinder was designed and implemented. The component design needed to interface with the transmission front housing and maintain position for itself and the slave cylinder. Figure 5.8 shows the final design. The through hole in the center was a clearance hole for the input shaft of the transmission to pass through. The recessed cutout in the back was a press fit onto the front case of the transmission. The front side has three equally spaced holes for slave cylinder mounting. The round slot in the front allowed the slave to sit flush on the mounting surface. The cutout on the side was necessary to allow for the incoming hydraulic line. The overall height was critical to ensure that the range of motion of the slave cylinder matched the necessary range of motion of the pressure plate, relative to the transmission.

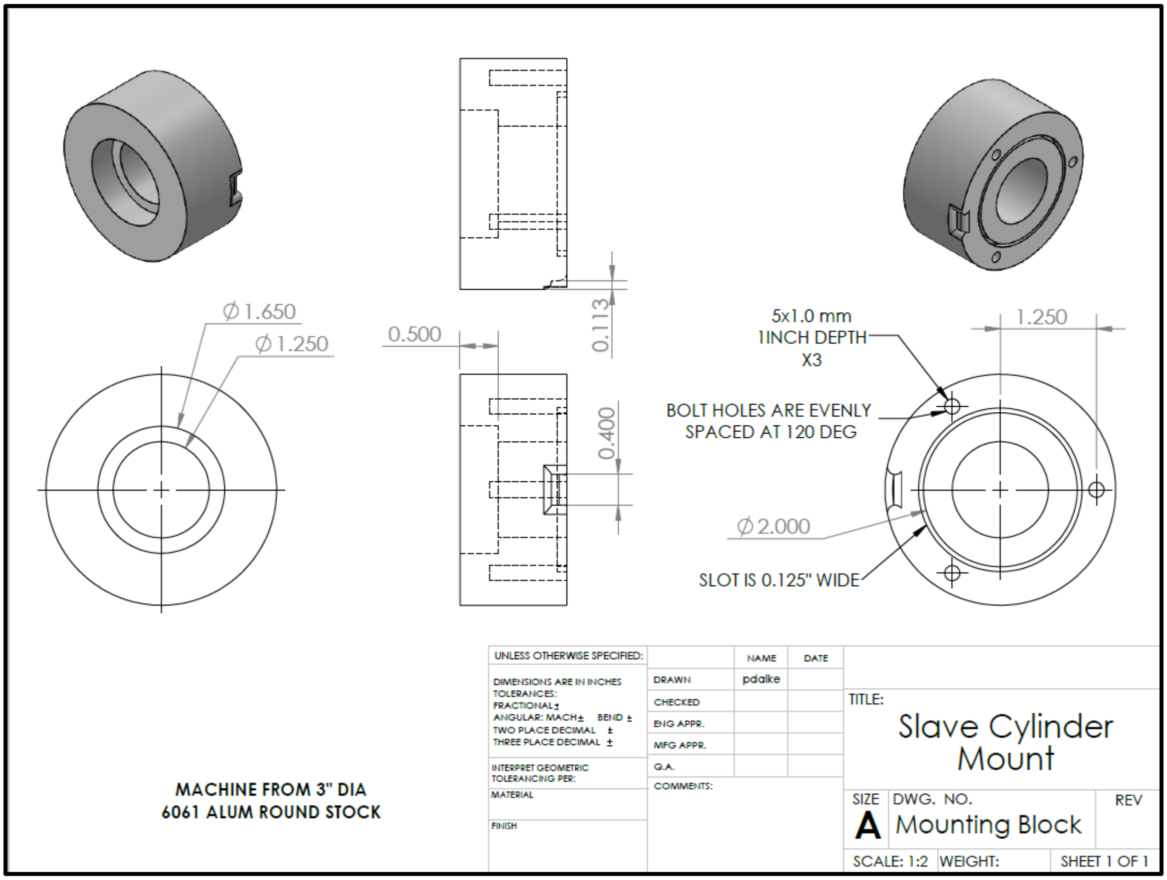

Figure 5.8: Engineering Drawing for Manufacture of Slave Cylinder Mount

Chapter 6. Validation and Verification

Moving up the right side of the V-Diagram, the components that were implemented in the component design and implementation stage are checked against the requirements previously defined for each subsequent subsystem. The validation and verification on the right side of the V-diagram is referred to as the third stage in the Systems Engineering Approach. This area of focus is highlighted in Figure 6.1.

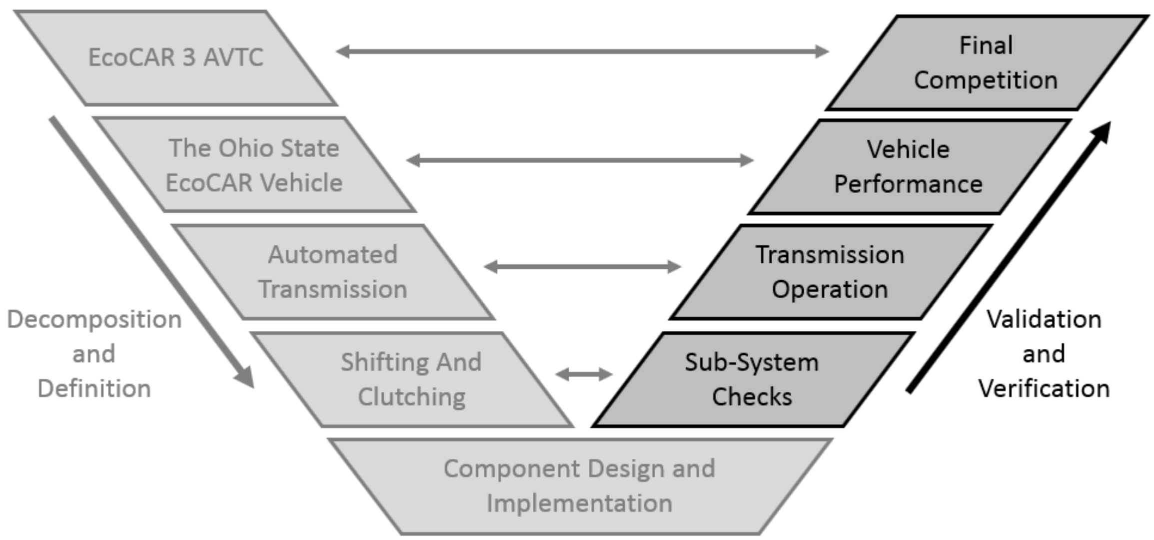

Figure 6.1: Validation and Verification Stage of the V-Diagram

6.1 Component Validation

The first step in validating the entire system was to validate the functionality of components. This included verification that the magnets, Hall Effect sensors, and clutch mounting met all requirements specified for those subsystems.

Magnets and Hall Effect Sensors

As a reference, the requirements for the magnets and Hall Effect sensors were:

(20) Modifications shall not impede the range of motion of the shifting block.

(21) Modifications shall not compromise the integrity of the transmission case.

(22) Modifications shall not create any potential fluid leaks.

(23) The sensors shall provide data in all possible positions of the shifting block.

To verify Requirement (20), the transmission was shifted into all gears manually and clearance was observed in all positions. There were no interferences found during any motion of the shifting block. Requirement (20) was satisfied.

To verify Requirement (21), the transmission was observed to have maintained its structural integrity after completion of the integration. No structural components of the transmission were modified during the implementation of the magnets and sensors. Requirement (21) was satisfied.

To verify Requirement (22), the transmission was filled with fluid and was rotated sufficiently to move fluid through the system. The floor was checked afterward and found to be free of leaked fluid. Requirement (22) was satisfied.

To verify Requirement (23), the output voltage of each Hall Effect sensor was measured in each of the final shifting block locations (in each gear) and in the left, right, and center neutral positions. This data was then used to create a voltage to coordinate transformation for each sensor. An example of the first sensor's measured voltages is given in Figure 6.2. All sensor mappings were combined to create a large look-up table that allowed the control system to adequately distinguish between all 5 potential shifter locations. The knowledge of current gear state in the transmission can be used to estimate expected passable torque through the transmission. Therefore, Requirement (23) was satisfied.

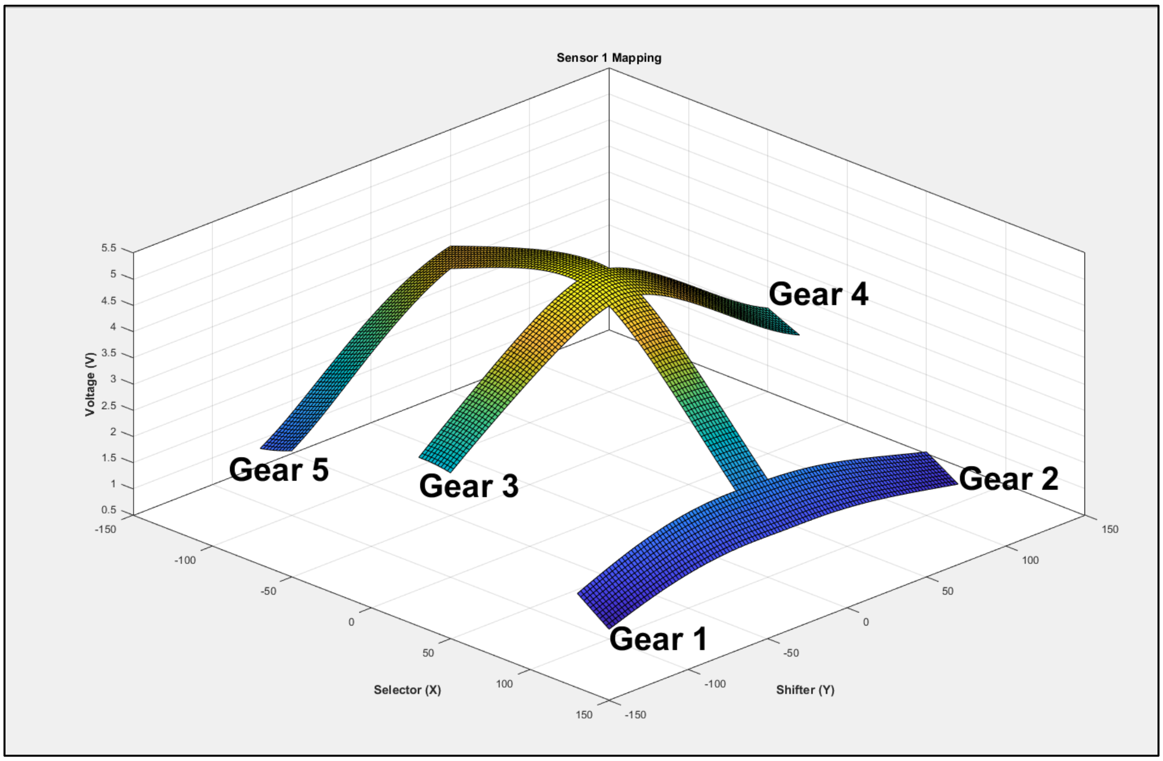

Figure 6.2: Voltage to Coordinate Transformation

Slave Cylinder Spacing

As a reference, the requirements for the slave cylinder spacing were:

(24) The mounting shall provide support for the slave cylinder during operation

(25) The mounting shall position the slave cylinder accurately so the range of motion of the slave cylinder and pressure plate correlate.

To verify Requirement (24), the slave cylinder was mounted onto the mounting block and assembled onto a transmission test rig. The mounting block held the slave cylinder securely in place both during static, non-operational checks and during hydraulic system pressure checks. The mounting continued to provide support during vehicle testing. Figure 6.3 shows the slave cylinder and mounting block assembled onto the transmission. Requirement (24) was satisfied.

To verify Requirement (25), the slave cylinder and mounting were assembled onto a transmission test rig and it was verified that the clutch was able to pass full torque when there was no pressure in the system and that the clutch was fully disengaged when the system was fully pressurized. Therefore, the range of motion of the slave cylinder completely encompassed the necessary range of motion of the pressure plate. Requirement (25) was satisfied.

The shifting and clutching subsystems are validated because all component level Requirements were satisfied.

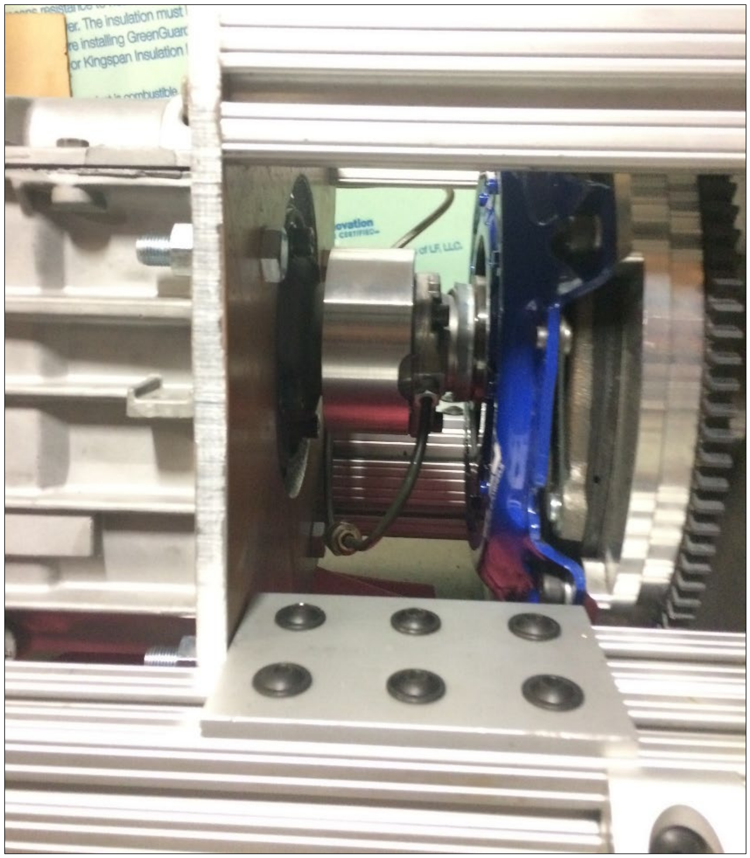

Figure 6.3: Benchtop Integration of Slave Cylinder Spacing Block

6.2 Subsystem Checks and Validation

The second step to validate the system was to verify that the transmission subsystems satisfy all requirements. At this level, the operation and functionality of each subsystem needed to be validated. This included tests for both automated shifting and clutching.

Automated Shifting

As a reference, the requirements for automated shifting were:

(14) The transmission shall shift into all gears.

(15) The transmission shall pass torque in a controlled manner.

(16) The transmission shall function reliably [6].

To verify Requirement (14), the transmission was set up in a test rig with the h-pattern converter, cables, and actuators. While on the bench top, the transmission was shifted repeatedly into all gears using the control feedback from the magnets and sensors. Requirement (14) was satisfied.

To verify Requirement (15), the transmission was commanded to shift into a specific gear and it was visually verified that the transmission had achieved a shift into the correct gear. If the transmission successfully shifted into the commanded gear, the torque output of transmission would be as expected based on gear ratio. This ensured that if a shifting action resulted in an incorrectly selected gear or a missed shift, the transmission controller would be aware of this fault. With this fault detection, the system would not attempt to pass any torque if the transmission was in an incorrect gear. Requirement (15) was satisfied.

To verify Requirement (16), the transmission was commanded to shift sequentially through all gears for ~5000 cycles and the number of failures was recorded. The system shifted into the correct gear with a 99.6% reliability. Requirement (16) was satisfied.

Automated Clutching

As a reference, the requirements for automated clutching were:

(17) The clutch shall disconnect the engine from the transmission.

(18) The clutch shall pass torque in a controlled manner.

(19) The clutch shall function reliably.

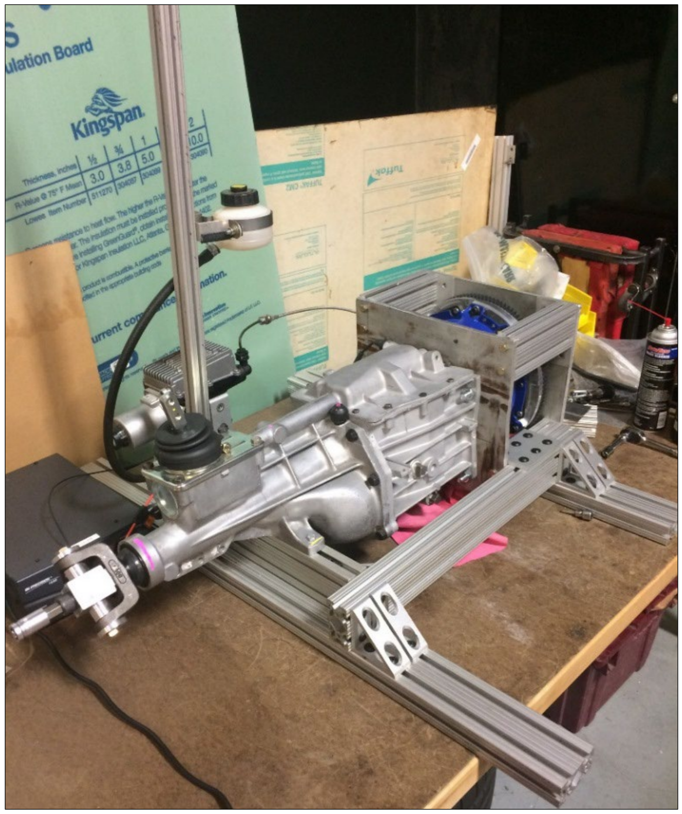

Figure 6.4: Benchtop Setup for Slave Cylinder Testing

To verify Requirement (17), the transmission was set up in the test rig seen in Figure 6.4. In this testing setup, the flywheel and transmission case were rigidly attached to the test rig mounting structure, preventing relative motion between the two components. While the slave cylinder was not pressurized, it was verified that the transmission output shaft could not spin, simulating the case when the clutch is fully engaged. The slave cylinder was then pressurized, and it was verified that the output shaft of the transmission could spin freely. This simulated the case where the clutch is disengaged. Requirement (17) was satisfied.

To verify Requirement (18), the torque transmittable by the clutch needed to be measured for the range of operating pressures of the slave cylinder. This was done using a modified

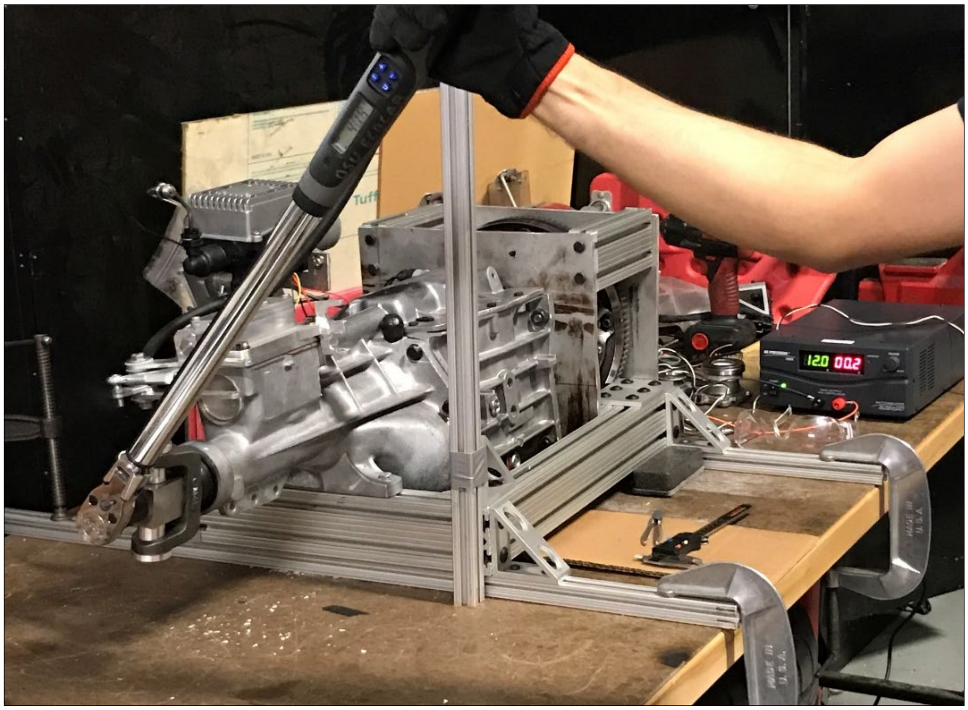

Figure 6.5: Example Testing Procedure for Data Collection

version of the test rig shown in Figure 6.4 to allow for a digital torque wrench to be attached, as seen in Figure 6.5. The calibration was performed by commanding a pressure to the hydraulic system feeding the slave cylinder and then applying torque to the digital torque wrench until the clutch disc began to slip. This test measured the torque transmittable through the system in two conditions: static and kinetic. For the value of static transmittable torque, the maximum torque value observed during a test was recorded. This reading occurred immediately prior to clutch disc slip. For the value of kinetic transmittable torque, the continuous torque applied to maintain clutch disc movement was recorded. The results of these tests are reflected in Figure 6.6. This relationship provided for prediction of transmittable torque through the system. Requirement (18) was satisfied.

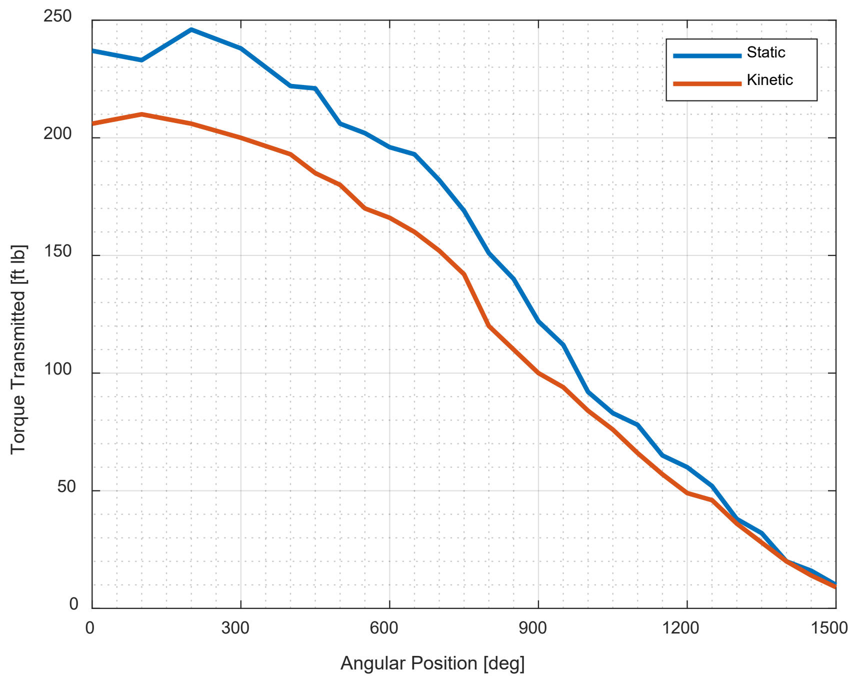

Figure 6.6: Static and Kinetic Torque Transmissibility Curves

To verify Requirement (19), the clutch system was subject to extensive bench testing, which included pressurizing and de-pressurizing the system repeatedly. No failures were observed after testing. A thorough check for fluid leaks was also performed to ensure that the hydraulic system was operating as intended. Requirement (19) was satisfied.

6.3 Automated Transmission Validation

As a reference, the requirement for the automated transmission was:

(13) The vehicle's transmission shall appear as an automatic to the driver. [3]

The third step to validating the system was to verify that the transmission satisfied its requirements. The automated transmission was validated through initial shakedown operation performed at the Transportation Research Center (TRC). To verify Requirement (13), the vehicle was driven under a variety of conditions and drive cycles. There was no interaction from the driver required for the transmission to select and shift gears. The Camaro utilizes the factory automatic pedal and shifter configuration. The methods for driving were identical to a standard automatic. The driver has no means of interacting with the transmission and the vehicle drove normally, thereby making the transmission appear as an automatic to the driver. Requirement (13) was satisfied.

6.4 Vehicle Validation

The fourth step was to verify that the vehicle met its requirements. The vehicle was validated through test driving performed prior to competition at TRC. Individual tests and system level calibrations were performed to evaluate and improve the vehicle's potential performance in competition events. The practice events were simulated as closely as possible to the competition events. As a reference, the OSU vehicle requirements were:

(6) The OSU vehicle shall meet or exceed all Team VTS targets.

(7) The OSU vehicle shall have an IVM – 60 time less than or equal to 7.5 seconds.

(8) The OSU vehicle shall maintain the level of driver-vehicle interaction present in the production Camaro.

(9) The OSU vehicle shall minimize noise, vibration, and harshness (NVH).

(10) The OSU vehicle shall improve drive quality and overall driving feel.

(11) The OSU vehicle shall minimize total vehicle mass.

(12) The OSU vehicle shall maximize efficiency.

IVM – 60 MPH Acceleration Test

To verify the vehicle's longitudinal performance, multiple IVM – 60 MPH runs were carried out. A VBOX was used to capture velocity data and accounted for a 1' rollout. The tests were carried out on the same stretch of road in both directions and the times were averaged to mitigate any slope or wind effects. The best vehicle IVM-60 time recorded during testing was 6.2 seconds. Requirement (7) was satisfied.

Consumer Appeal Test

To verify the vehicle's drive quality, the vehicle was driven both casually and aggressively along various road courses, attempting to capture any odd behavior that could potentially be observed by a judge. Any non-normal behavior was logged and calibrated to remove or reduce the impact of such behavior on drive quality. Requirements (8), (9), and (10) were satisfied.

Emission and Energy Consumption Test

To verify the vehicle's emissions and energy consumption, the vehicle was driven through the pre-determined competition E&EC cycles to ensure that the optimal gear could be selected for each operating condition that the vehicle could potentially experience. This process was used to optimize the vehicle performance in the emissions and energy consumption tests. Requirements (11) and (12) were satisfied.

Vehicle Technical Specifications

To verify the vehicle's adherence to the Team VTS targets, tests were performed to evaluate the vehicle's ability in all areas. Dynamic targets were verified through driving testing at TRC. Static targets were verified through checks performed while the vehicle was stationary. All final VTS specifications, as recorded by the team during pre-competition testing, are given in Table 6.1. All "As Tested" VTS met or exceeded the Team's VTS targets. Requirement (6) was satisfied.

Table 6.1: Team VTS as Tested Compared to Targets

VTS	Units	Targets	Team VTS	As Tested
Acceleration, IVM–60 mph	sec	5.9	7.5	**6.2**
Acceleration, 50–70 mph (Passing)	sec	7.3	8.0	**3.2**
Braking, 60–0 mph	ft	128	120	**122**
Acceleration Events Torque Split (Front/Rear)	%	RWD	RWD	**RWD**
Lateral Acceleration, 300 ft. Skid Pad	G	0.85	0.90	**0.94**
Double Lane Change	mph	55	55	**55**
Highway Gradeability, @ 20 min, 60 mph	%	6%	6%	**6%**
Cargo Capacity	ft^3	N/A	2.4	**3.1**
Passenger Capacity	#	4	4	**4**
Curb Mass	kg	N/A	1903	**1913**
Starting Time	sec	2	2	**<2**
Total Vehicle Range	mi	N/A	273	**275**
CD Mode (blended/EV)		N/A	EV	**EV**
CD Mode Range	mi	N/A	44	**40**
CD Mode Total Energy Consumption	wh/km	N/A	220	**243.3**
CS Mode Fuel Consumption	wh/km	N/A	558	**617**
UF-Weighted Fuel Energy Consumption	wh/km	N/A	504	**411**
UF-Weighted AC Electric Energy Consumption	wh/km	N/A	193	**206**
UF-Weighted Total Energy Consumption	wh/km	700	697	**617**
UF-Weighted Total Energy Consumption	mpgge	30.0	43.3	**52.9**
UF-Weighted WTW Petroleum Energy Use	wh PE/km	420	150.9	**120**
UF-Weighted WTW Greenhouse Gas Emissions	g GHG/km	225	300	**204**

6.5 Competition Validation

The final validation of the system was the performance of the team and vehicle at the Year 4 Competition. As a reference, the competition level requirements were:

(1) Competition teams shall strive to win in each of the four years of competition.

(2) The vehicles shall have sufficient longitudinal performance.

(3) The vehicles shall have adequate drive quality.

(4) The vehicles shall be fuel efficient.

(5) The OSU team shall place in the top 5 in each year of the competition.

The final results of the relevant competition events are given in Table 4.1Table 6.2. Requirement (2) was satisfied with a 7th place finish in the IVM – 60 Event. Requirement (3) was satisfied with a 1st place finish in the Consumer Appeal Event. Requirement (4) was satisfied with top 5 finishes in all E&EC Events. Requirements (1) and (5) were satisfied with a 1st place finish overall for Year 4 of the Competition.

Table 6.2: Relevant Final Competition Scores and Ranks

Event	Score	Rank
IVM – 60 MPH	13.9/20	7th
Consumer Appeal	45/45	1st
EEC UFW Total Energy Consumption	30/30	1st
EEC UFW WTW Petroleum Use	30/30	1st
EEC UFW WTW GHG Emissions	29.5/30	2nd
EEC UFW WTW Criteria Emissions	21.4/30	4th
Overall Competition Final	**895/1000**	**1st**

Chapter 7. Conclusions

In conclusion, the systems engineering approach was used to ensure that the vehicle as designed accomplished the goals it was intended to accomplish. The competition was decomposed into very specific design spaces, solutions were engineered to solve specific problems, and competition point return-on-time/money-investment was maximized. At the end of this research, all 25 requirements were satisfied. The final design validated the highest-level requirement and therefore, the design is considered a success.

7.1 Future Work

Looking forward to future competitions and projects, it is advised to apply the systems engineering approach to formally decompose the high-level system and define requirements for each level. This is especially useful if the project must be passed on to a different team of engineers. The formal definition of requirements aids in the communication of the original design intent, helping to reduce rework because all team members are aware of what the design is intended to accomplish at each level. The levels of requirements and validation also assist in the handing-off of a sub-project as it moves through the V-diagram. This ensures that the engineers defining the system, the engineers designing components/solutions, and the engineers testing and validating components/subsystems are all working towards the same goal. This will help to minimize cost and time of a project, thus maximizing its success.

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Appendix A. Full List of Requirements

This is a full list of Requirements for the vehicle system.

(1) Competition teams shall strive to win in each of the four years of competition.

(2) The vehicles shall have sufficient longitudinal performance.

(3) The vehicles shall have adequate drive quality.

(4) The vehicles shall be fuel efficient.

(5) The OSU team shall place in the top 5 in each year of the competition. [5]

(6) The OSU vehicle shall meet or exceed all Team VTS targets.

(7) The OSU vehicle shall have an IVM – 60 time less than or equal to 7.5 seconds. [4]

(8) The OSU vehicle shall maintain the level of driver-vehicle interaction present in the production Camaro.

(9) The OSU vehicle shall minimize noise, vibration, and harshness (NVH).

(10) The OSU vehicle shall improve drive quality and overall driving feel.

(11) The OSU vehicle shall minimize total vehicle mass.

(12) The OSU vehicle shall maximize efficiency.

(13) The vehicle's transmission shall appear as an automatic to the driver. [3]

(14) The transmission shall shift into all gears.

(15) The transmission shall pass torque in a controlled manner.

(16) The transmission shall function reliably [6].

(17) The clutch shall disconnect the engine from the transmission.

(18) The clutch shall pass torque in a controlled manner.

(19) The clutch shall function reliably.

(20) Modifications shall not impede the range of motion of the shifting block.

(21) Modifications shall not compromise the integrity of the transmission case.

(22) Modifications shall not create any potential fluid leaks.

(23) The sensors shall provide data in all possible positions of the shifting block. [6]

(24) The mounting shall provide support for the slave cylinder during operation

(25) The mounting shall position the slave cylinder accurately so the range of motion of the slave cylinder and pressure plate correlate.